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6. AUTHOR(S)
Karen E. Roth and Shelby K. Barrett

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFRL/RISB
525 Brooks Road
Rome NY 13441-4505

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFRL/RISB
525 Brooks Road
Rome NY 13441-4505

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14. ABSTRACT
A virtual wind tunnel for command and control systems has long been the 'holy grail' of many research and development communities. This paper explores the early design, development and integration of a software testbed for Command and Control (C2) systems called the Command and Control Wind Tunnel. This synthetic environment is intended to model current and future C2 environments, allowing prototype C2 technologies and designs to be tested and evaluated, in a near realistic environment. Building a comprehensive system to represent C2 has many challenges. The C2 problem space is continuously evolving, increasingly complex and fluid. One must consider many factors, including people, processes, systems, data, and relationships, in order to model it. This system of systems must loosely couple disparate models and simulation engines; enable the use of real world data across multiple models expressed in different modeling languages; and still allow for rapid system configuration and integration. At the end of this paper the reader will understand the goals and ideals of the C2 Wind Tunnel, what technologies are going into the design of the Wind Tunnel, the status of the current prototype, and the next planned steps to achieve the C2 Wind Tunnel environment.

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Command & Control Wind Tunnel Integration and Overview

Karen E. Roth
Shelby K. Barrett
Air Force Research Laboratory
AFRL/RISB 525 Brooks Road
Rome, NY 13441-4505
United States
315-330-7878, 315-330-1447
Karen.Roth@rl.af.mil, Shelby.Barrett@rl.af.mil

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1. Introduction

The notion of a C2 Wind Tunnel was introduced in 2003, by the then Air Force Research Laboratory's Chief Technologist, Dr. Tom Cruse, "as a means of evaluating human-in-the-loop Command and Control technologies." Preliminary prototypes and component technologies would be individually tested in their specific "tech" simulations. When they showed promise they would be integrated into command and control systems and evaluated using the C2 Wind Tunnel. This would provide valuable data on the utility of the system and guidance for further development. [1] Dr. Cruse pursued this vision with a commissioned study led by Shankar Sastry from Berkley, Janos Sztipanovits from Vanderbilt University, and Sharon Heise of the Air Force Office of Scientific Research (AFOSR).

Since then the concept has had the benefit of cross domain collaboration from many universities and government research labs. The C2 Wind Tunnel combines existing commercial, open source, Government off-the-shelf (GOTS) and in-house software, models, and utilities, allowing for the use of 'best tool available' solutions.

The universities involved include: Vanderbilt University's Institute for Software Integrated Systems (ISIS), George Mason University's System Architectures Laboratory (SAL), Carnegie Mellon University's Center for Computational Analysis of Social and Organizational Systems (CASOS), University of California, Berkeley's Berkeley Aerobot Team (BEAR) and the Naval Postgraduate School's Modeling, Virtual Environment and Simulation (MOVES) Institute. Primary sponsorship of the universities came from the Air Force Office of Scientific Research (AFOSR). Technologies developed at Air Force Research Lab Information Directorate (AFRL/RI) have also been integrated into the C2 Wind Tunnel. AFRL/RI and the Air Force Information Operations Center (AFIOC) will be involved at the operational testing level.

2. Behind the C2 Wind Tunnel

The C2 Wind Tunnel serves the same purpose as conventional wind tunnels built to gather aerodynamic data. However, instead of having a large physical structure, the C2 Wind Tunnel is a networked, synthetic environment. The goal of the C2 Wind Tunnel is to develop a controlled environment of loosely-coupled, heterogeneous models of the systems, the environment, the humans and the interactions in a command and control environment, for the purpose of testing and evaluating prototype C2 technologies, and designs, in a manner similar to real world conditions.

The C2 Wind Tunnel is a model-based, experiment integration environment consisting of several different layers, each with unique implications as shown in Figure 1.

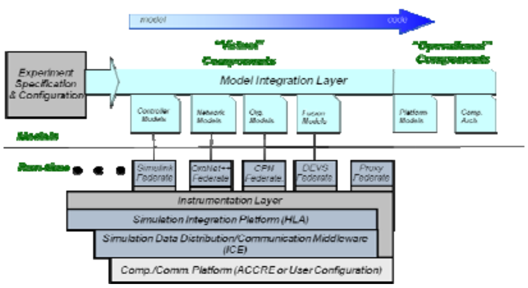

Figure 1: C2 Wind Tunnel Architecture [4]

First, a flexible, backend framework has been designed to allow for the rapid configuration and integration of new or different pieces. The ability to integrate different models allows us to use the most appropriate models – based on the level of fidelity needed to conduct an experiment and obtain best answers.

Second, an instrumentation layer provides the ability to analyze decisions in real time for more dynamic feedback. It also provides a controlled environment with the ability to collect and measure data, monitor the simulation variables of interest and conduct post simulation, analytical studies. The ability to combine models in real time and make dynamic decisions opens the possibility of using the C2 Wind Tunnel environment during a crisis situation, giving our commander's greater insight into a situation.

Third, a simulation integration platform layer is necessary to bring together the different simulation pieces. This layer is currently the High Level Architecture (HLA).

Fourth, a data distribution and communication middleware layer allows data to be received and transmitted between the different components.

The last layer is the system platform layer, allowing user configuration and experimentation on different platform architectures, such as High Performance Computers, Parallel and Distributed computers.

3. The Technologies of the C2 Wind Tunnel

The C2 Wind Tunnel consists of technologies and algorithms developed at several top universities; both independently and in collaboration. The C2 Wind Tunnel currently contains high fidelity physics models for UAVs, developed at Berkeley; a Generic Modeling Environment (GME), developed at Vanderbilt University; human organization modeling with Colored Petri Nets, developed by George Mason University; the Discrete Event System Specification (DEVS)-JAVA from University of Arizona; and a social networking model, ORA, from Carnegie Mellon University.

Also integrated into the C2 Wind Tunnel are many open source projects allowing for more cost effective and more easily modified code. Some of the open source projects in use are Portico-0.8, an open source HLA run-time infrastructure implementation, and OMNeT++, an open source, component-based simulation package designed for modeling communication networks, multi-processors and other distributed systems.

The underlying architecture of the C2 Wind Tunnel allows one to quickly try new algorithms, simulation technologies and models from a variety of sources to find the best mix to find the best answer.

3.1 Model Integration & Simulation Configuration

In order to bring existing and new models into the C2 Wind Tunnel environment, a separate tool must be used. In this case it is the Generic Modeling Environment (GME). GME is a configurable toolkit for creating domain-specific modeling and program synthesis environments. The configuration is accomplished through metamodels specifying the modeling paradigm (modeling language) of the application domain. The modeling paradigm contains all the syntactic, semantic, and presentation information regarding the domain; which concepts will be used to construct models, what relationships may exist among those concepts, how the concepts may be organized and viewed by the modeler, and rules governing the construction of models. The

modeling paradigm defines the family of models that can be created using the resultant modeling environment. [5]

Operationally, GME provides the ability to add existing models, some more easily than others. It uses a UML type language to define the components and their interfaces. New models will require interactions be defined and mapped to other models in the simulation. Access to the underlying timing mechanism of the model is required for integration purposes. Once a model has been defined, any operator can easily use the user interface to drag and drop icons representing these different models to define a new simulation or modify and existing one. All the scripts can then be automatically generated to run the simulation. The learning curve is fairly shallow for one with an understanding of basic modeling languages. Once the interactions are defined and mapped much of the configuration overhead is removed.

3.2 Run-Time Infrastructure

The C2 Wind Tunnel uses HLA; a Department of Defense (DoD) approved and mandated standard reference architecture for modeling and simulation. A variety of existing and developing gateways exist to aid in translating between HLA and other protocols like Distributed Interactive Simulation (DIS). The run-time infrastructure currently integrated into the C2 Wind Tunnel is Portico, an open source implementation freely accessible to all involved parties. Only a few of its capabilities are implemented at this time. AFRL is evaluating Portico against other run-time infrastructures like RTI-S, which is government controlled, and RTI NG Pro, which is industry controlled.

3.3 Current Models

The network models were designed in OMNeT++ using INET. OMNeT++ is a communication focused simulation environment, chosen for its flexible architecture. OMNeT++ is also public-source with an open architecture, making it easier to integrate into the already existing environment. The INET framework is a plug-in for OMNeT++ that contains models for IP, TCP, UDP, PPP, Ethernet, and other protocols and is also open-source.

Matlab, with Simulink and the Control System Toolbox, are used to model the physics of Unmanned Aerial Vehicles (UAVs). The universities have also used Virtual Reality Toolbox for some functions. AFRL is using C-based code to provide similar functionality. An upcoming release will include autonomous UAVs using University of Arizona developed models.

The command and control workflow is modeled with Colored Petri Nets (CPN). CPN is a language for the modeling and validation of systems in which concurrency, communication, and synchronization play a major role. It is a discrete-event modeling language combining Petri Nets with the functional programming language Standard ML. A CPN model of a system is an executable model representing the states of the system and the events that can cause the system to change state. [2] This is a powerful tool for modeling the intricate workflow processes found in a C2 environment.

The last major modeling tool integrated is ORA. ORA is a social network analysis tool that detects the risks or vulnerabilities of an organization's design structure. The design structure of an organization is the relationship among its personnel, knowledge, resources, and task entities. [3] Currently ORA's capabilities are limited in the current model. The next update promises a more robust model. This tool will be used to evaluate the effects of having knowledge of an organization's structure and relationships when making C2 type decisions.

3.4 Visualization

Google Earth, using the Google Earth Plugin, was originally used for visualization of the UAV, UAV Operator and God's Eye View perspectives of the simulation. After transition to AFRL, it was determined that it was not stable when taken off of the network and would require a prohibitively high licensing fee to use it in the AFRL environment.

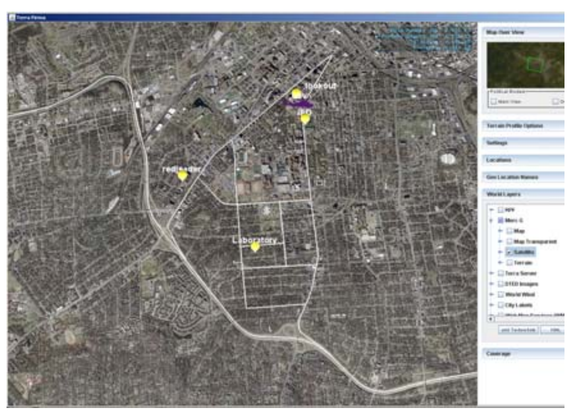

Figure 2: C2 WIND TUNNEL_View, JVIEW-based visualization

This component was replaced with an AFRL-developed visualization, created with an in-house

API known as JVIEW; shown in Figure 2. This is an active development project specifically designed to address rapid visualization prototyping, correctness, efficiency and effectiveness. It allows the use of a variety of datasets including Digital Terrain Elevation Data (DTED), satellite data and weather data. This API has also been made available to the universities to use as well.

The universities have also made use of Delta3D an open source game and simulation engine, developed at the MOVES Institute, located at the Naval Postgraduate School in Monterey, California. This may be included more extensively in future releases. It should be noted that Delta3D offers features like HLA, After Action Review (AAR), large scale terrain support and Sharable Content Object Reference Model (SCORM) Learning Management Systems (LMS) integration.

4. The Challenges of the C2 Wind Tunnel

4.1 Concept Challenges

Creating a complex system of systems comes with many challenges. Weaving together diverse, distributed systems across varying domains and functional areas is not for the faint hearted, due to the number of data types, formats, and fused information needed to provide a 'whole world' scenario. The conclusion is that effectively integrating virtual, live and constructive simulations, both discrete and stochastic, is a complicated process. However, with great complexity comes great power.

C2 consists of people, processes, communications, organizations, and systems. The C2 Architecture is ever-changing to adapt to new challenges. There are many intricacies, often known only by a few. Documentation is often sparse and difficult to locate, if it exists at all. Modeling existing C2 is a challenge in and of itself. Modeling the existing, while maintaining the flexibility to integrate new tools and process models and reconfigure the existing models as necessary is an even larger effort. Integration practitioners must deal with the issues of complexity, diversity, heterogeneity, scalability and agility.

Keeping pace with the rapid change of technology, capturing and maintaining knowledge and skills, identifying or developing accurate models, defining useful metrics, maintaining sufficient infrastructure to support heterogeneous systems, distributed environments, communication networks, and multi-level security are challenges faced in every research area, but more so in the C2 environment because we are often bringing many of the diverse research areas together in an attempt to create a cohesive 'God's Eye' view.

The level of fidelity required to make good C2 decisions is as varied as the types of data and decisions made by a C2 commander. Good decision making requires knowledge of a variety of domains and functional areas and the skill to determine what level of detail is required to make decisions. Capturing and codifying this ability will allow experimentation with different levels of fidelity. Often people do not know what tools they need or what is possible, other times they think they need specific tools without appreciating the cost of ownership versus the benefit provided. A testbed environment for prototypes helps everyone to touch and see the applicability of a new tool or process design. This kind of testbed also lets one test various tool combinations to see what augments and what detracts or duplicates another, supporting refinements in the early stages of development. Opportunities for the 'aha' of discovery and unexpected results give developers, project managers, and operators greater insight and feedback early in the development process. The real power of the C2 Wind Tunnel lies in having enough interoperability, functionality and standards in place so that C2 application and process developers can bring in an outside system and test it without being required to understand the architecture and design of the testbed.

4.2 Other Challenges

A major challenge has been in transitioning and bringing together each of the separate university pieces into a laboratory environment, in compliance with AFRL information assurance directives for approved systems and software. There is a long timeline to add new products to the approved list and products may be obsolete or not 'best choice' by the time they are approved. The university environment is very different from the government's and it is often more difficult to set things up in the government lab similar to the university. The government is required to comply with mandated network security directives, system specifications and commercial licensing requirements. Universities often have access to free or reduced academic licenses that are costly for commercial purchase. Scalability is another transition challenge due to the increased size and number of entities in government simulation experiments. They are often much larger than the universities ever anticipated. Ongoing

collaboration and communication can assist in ironing out these difficulties.

Another challenge for the Laboratory is to incorporate and test the existing simulation standards, providing feedback on the experience to the appropriate community. Using these standards will allow more scenarios to be brought into the C2 Wind Tunnel environment, but may provide added difficulty to an already complex environment. Potential standards to incorporate are the Military Scenario Definition Language (MSDL), the Coalition Battle Management Language (CBML) and SCORM-Simulation Interface Standards.

Early transition and integration experiences have highlighted the initial framework's fragility. Much can be corrected and is being corrected by allocating time for good software management processes, including shared configuration control, test sets, and training. These early stumbling blocks are being overcome with additional manpower, better communication and a more defined development processes.

4.3 Payoff

Despite all of these challenges, the C2 Wind Tunnel has the potential to have a large payoff in terms of testing, not only for functionality, but also for the effectiveness of prototype systems. The opportunity exists for testing in a fraction of the time that current testing procedures allow leading to a higher defect detection rate. The C2 Wind Tunnel will have the ability to analyze human/machine interfaces from both manned and unmanned teams. This allows the gathering of human effectiveness metrics and efficiency data. How easy is the system to learn? How fast does it respond? How easily can it be adapted to different types of users?

The C2 Wind Tunnel will also be able to easily evaluate machine/machine interfaces and the effectiveness of their interoperability with each other. Is data getting transferred across domains appropriately and being translated into different languages? Perhaps one of the biggest challenges is that the C2 Wind Tunnel must also have the ability to independently self assess, not only in the models to determine whether or not the software is responding appropriately, but also detect whether or not the warfighter or commander is receiving the best possible view of the data.

5. Current Status and Future Plans

5.1 Status

The C2 Wind Tunnel is currently in the early prototype stage. The basic architecture has been determined and several of the university-developed models have been integrated and demonstrated with a C2-focused scenario. The current components included are shown in Figure 3.

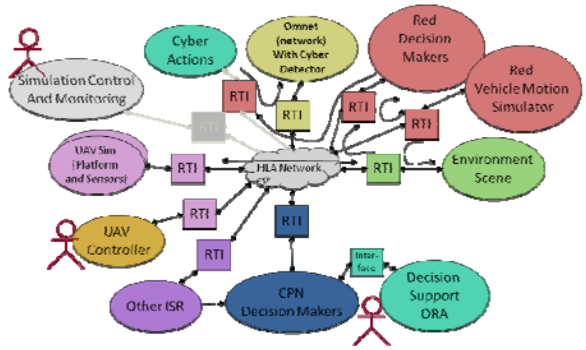

Figure 3: High Level View of C2 Wind Tunnel Components for Demonstration [6]

A recent demonstration with these components showed that it is technically feasible to loosely couple different models built using different modeling languages, that it is operationally practical to configure diverse multi-model simulations to address complex multi-domain C2 issues in a CAOC, and that it is feasible to address operational and tactical issues in an integrated manner. [4]

The demonstration scenario was developed to illustrate the C2 Wind Tunnel capabilities for using multiple, loosely-coupled models in support of operations; representing blue-red interactions (two-sided), including tactical and operational decision-making. The time-sensitive operations scenario provides red and blue objectives and courses of action, and red and blue assets. Red follows a script but may react to blue's actions. Blue may anticipate and react to red's actions. The current architecture supports the inclusion of one or many human-in-the-loop playing different roles; from operator to decision maker.

Demonstration results prove the architecture is feasible and sufficiently functional to begin experimentation and to begin expanding it with additional models. The initial prototype system is being distributed to other locations for further demonstrations, additional component integration and in-house testing. AFRL/RI has taken on the task of integrating the C2 Wind Tunnel set up in a research and operational environment.

5.2 AFRL/RI Status

AFRL/RI has successfully set up the systems and software on seven workstations running a combination of Windows XP and Fedora 9 operating systems, on a standalone network via 10/100 Ethernet switch. They have also started the integration of the JVIEW based component into the system. It receives the same information the Google Earth visualization did and runs off line. Other current work includes working to understand and use the scenario deployment features available in GME to integrate the JVIEW based visualization component as an HLA federate.

At this time, some basic data is logged in flat files. Vanderbilt University is in the process of defining a database schema for capturing and collecting a variety of simulation-specific and model-specific data. Presently, the limited data collection has restricted the ability to do more than cursory analysis. As this project moves forward, the ability to perform rigorous analysis will be added.

5.3 Next Steps

An immediate next step is to take the initial, heavily scripted, basic demonstrations to the next level with more robust and dynamic model implementations to more reliably test the system and models. This will include the benchmarking and evaluation of the current models and glue pieces.

Other endeavors include the integration of OPNET for more mature network models, Emulab for network emulation, and integrating with WebTAS, a front end for some of the operational data found in Theatre Battle Management Core Systems (TBMCS).

WebTAS integration will be the first step toward integrate existing data sources and environments into the C2 Wind Tunnel. The principle of the C2 Wind Tunnel is not just to create another simulation system, but one capable of pulling existing information and data to produce more realistic results. Another area under development is the definition of valid C2 metrics. The C2 Wind Tunnel must be able to understand and evaluate each system against the appropriate metrics to give the designers and managers a benchmark for the readiness of the system for fielding.

Testing the C2 Wind Tunnel on more advanced and prototype computing architectures is another area being investigated by AFRL/RI. This is important for two reasons. First, the C2 Wind Tunnel system is going to be a very resource intensive product and steps should be taken now to make this burden more manageable. The key to a successful product rests on the ability to provide reliable data at reasonable speeds. Second, being able to handle these architectures will be important for being able to manage future unknowns. Different types of architectures being investigated include parallel and distributed computing, cell clusters, and HPCs.

AFRL, in particular, is also interested in ensuring that the C2 Wind Tunnel is open to a wide variety of models from different disciplines to gain the greatest insight and to leverage the investment across all ten of its directorates like Munitions, Air Vehicles, Directed Energy, and Space Vehicles.

5.4 Future Goals

C2 environments require adaptability through flexibility. Our plan is to use the C2 Wind Tunnel to seek optimal solution sets and support technology investment assessments. The C2 Wind Tunnel will use complex joint mission scenarios to explore, demonstrate, evaluate and document the capabilities of new and existing tools, methods, techniques and run-time technologies. Working toward a more robust system that the operators can use logically and efficiently will encourage collaboration between operators and technologists. The C2 Wind Tunnel may also be used as a training tool.

6. Conclusion

This paper has introduced the concept of the potential for a Command and Control Wind Tunnel where prototype C2 systems may be placed into this software environment revealing potential benefit to the warfighter. The goal of the C2 Wind Tunnel is to design a system of systems that has the ability to support a wide range of models, modeling languages, and simulation engines, function across different languages and technologies, with sophisticated evaluation mechanisms, in a timely manner with little set-up time. This is a tall order, that researchers from across academia and the government have come together to solve together.

Currently, the C2 Wind Tunnel is in prototype and initial demonstration stages, with an initial functioning architecture in place. Several simulation pieces have been successfully integrated and basic models and scenarios have been exercised. The next steps are to finish adding all proposed architecture pieces and build more extensive models. This will be able to show not only the power of the C2 Wind Tunnel, but help to reveal potential problems. From there it will be easier to expand into new domains and explore different architectures and models.

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Author Biographies

KAREN E. ROTH is an Associate Computer Engineer at the Air Force Research Laboratory in Rome, NY where she works on the analysis of next-generation simulation capabilities for Command and Control systems. Other research interests include High Performance Computing and Systems and Software Engineering. She received her Bachelor of Science in Software Engineering from the Rochester Institute of Technology and is currently finishing a Masters of Engineering in Systems Engineering from Cornell University.

SHELBY K. BARRETT is an Associate Computer Scientist at the Air Force Research Laboratory in Rome, NY where she works on next-generation simulation capabilities. Other research interests include Distributed and Collaborative Workflows, Software Engineering and Human-computer Interaction. She received her Bachelor of Science in Computer and Information Sciences from the State University of NY.